Enhancing the International X-ray Observatory

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ABSTRACT

Over the last two years, we have studied system concepts for the International X-ray Observatory (IXO) with the goal of increasing the science return of the mission and to reduce technical and cost risk. We have developed an optical bench concept that has the potential to increase the focal length from 20 to 25 m within the current mass and stability requirements. Our deployable bench is a tensegrity structure formed by two telescoping booms (compression) and a hexapod cable (tension) truss. This arrangement achieves the required stiffness for the optical bench at minimal mass while employing only high TRL components and flight proven elements. The concept is based on existing elements, can be fully tested on the ground and does not require new technology.

Our design further features hinged, articulating solar panels, an optical bench fully enclosed in MLI and an instrument module with radially facing radiator panels. We find that our design can be used over a wide range of sun angles, thereby greatly increasing IXO's field of regard, without distorting the optical bench. This makes a much larger fraction of the sky instantaneously accessible to IXO.

Keywords: IXO, X-ray observatory, deployable structures, system engineering

1. INTRODUCTION

The International X-Ray Observatory (IXO) is a 20 – 25 m deployable X-ray observatory, with a planned launch in 2021. IXO is collaboration between NASA, ESA, and JAXA and supersedes NASA's Constellation-X concept and ESA's XEUS concept. For NASA, IXO will be the successor to the Chandra X-Ray Observatory, with an order of magnitude increase in effective area and spectral resolving power up to two orders of magnitude higher than any current X-ray imaging mission.

The key challenges for IXO are a close to 100-fold increase in effective area of the mirror assembly and a doubling of the focal length compared to the Chandra observatory, all achieved at roughly the same total system mass. In 2008 we began to develop an IXO system concept that could be built with minimal cost and schedule risk. Our approach builds on and takes advantage of the extensive mission studies performed for NASA at the Goddard Space Flight Center [1,2,3,4], is informed by ESA design studies and brings the unique experiences and capability of Northrop Grumman Aerospace Systems to this task.

2. DESIGN OVERVIEW

The main elements in our IXO concept, see Figure 1 for an overview, are the flight mirror assembly (FMA) on one end and the instrument module at the opposite end of a precision deployable optical bench. The optical bench, constructed from graphite tubes has a fixed and an extendible section. The spacecraft avionics are located on modular fold-down panels mounted on a hexagonal truss structure on top of the fixed section of the optical bench. The spacecraft components are thermally isolated from the bench through multi-layer insulation. The design includes articulating solar panels that face outward in the stowed configuration to provide power prior to deployment. The single-axis solar array drive assembly (SADA) enables us to point the telescope over a wide range of sun angles, limited only by thermal concerns and sun exclusion zones required by the x-ray mirror. The high gain communication antenna has one of its two pointing gimbal axis parallel to the SADA axis providing Earth tracking over large sun angle changes. The deployable bench also includes several deploying field stops that cut-down on background due to non-imaged x-rays. The entire structure will be wrapped in a light-tight, accordion multi-layer MLI insulation for thermal control and to block out stray light.

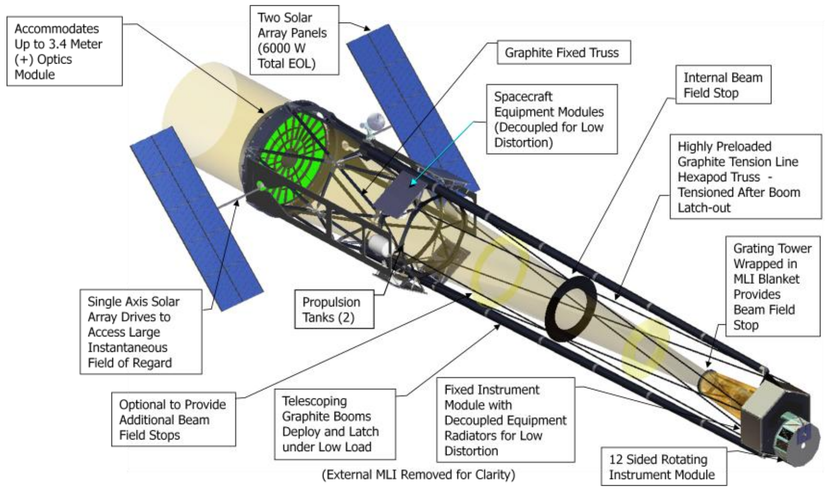


Figure 1. Overview of the NGAS concept for IXO – shown with external MLI tent removed for clarity

3. DEPLOYABLE OPTICAL BENCH USING TENSEGRITY STRUCTURE

Our concept for the deployable optical bench makes innovative use of a tensegrity structure, well established for decades in architecture. Tensegrity is a property of structures that base their integrity on a balance between tension and compression. These structures achieve very high stiffness at very low masses. For IXO, see Figure 2, the compression elements are two telescoping booms that are deployed without load from tension lines. Once the booms are fully deployed and latched, tension lines are tightened with linear actuators to stiffen the structure. The light weight structure is built up from near-zero CTE material and is maintained at a stable temperature. The extensible section of the optical bench for IXO sits on top of a fixed "elephant stool" truss, a design repeatedly flight proven and chosen for its high strength to mass ratio.

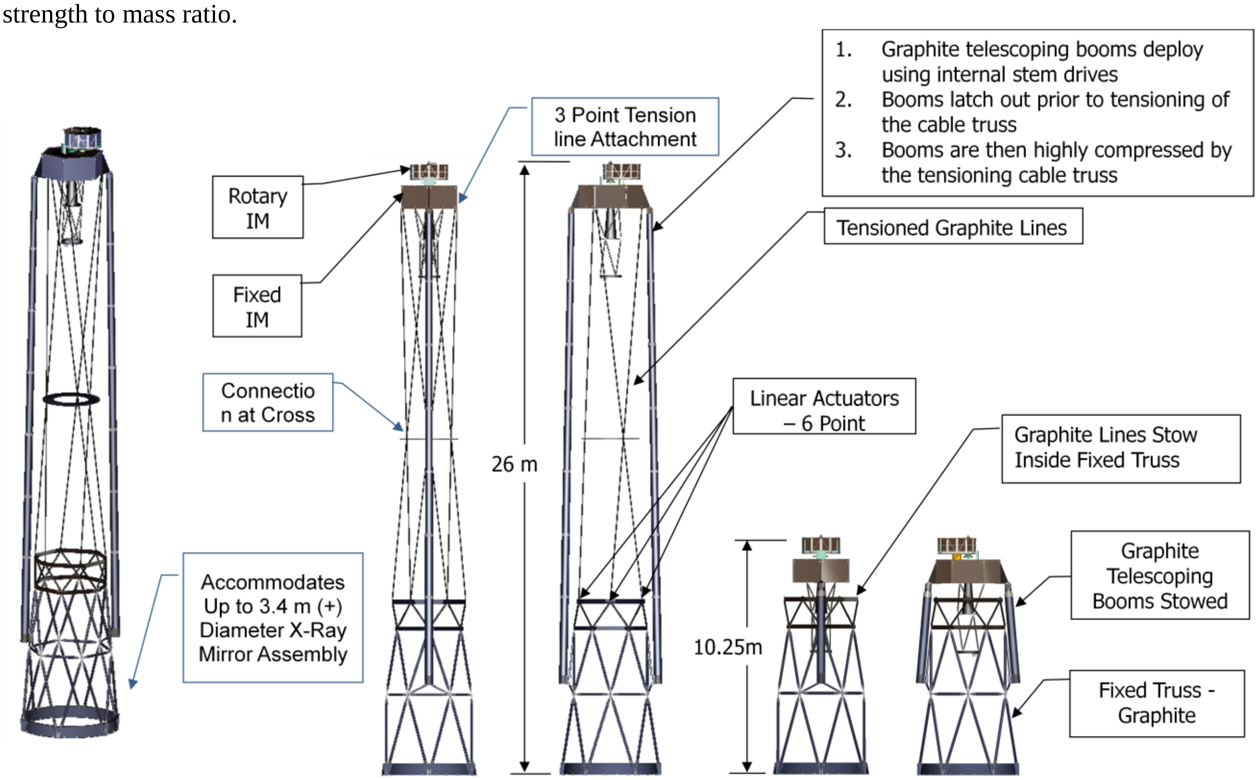


Figure 2. IXO deployable tensegrity structure for the optical bench assembly.

4. INSTRUMENT LAYOUT

Our concept for the instrument layout is driven by the desire to enable a large range of sun angles and make thereby a large portion of the sky accessible at any given time. We have addressed power generation by incorporating articulating solar arrays and are now concerned about the thermal requirements (see section 6 for a detailed discussion). Four IXO science instrument are located on a rotating platform that moves the commanded instrument to the focal point of the FMA, see Figure 3. We also indicate a fixed location for the detector of the X-ray Grating Spectrograph that is always in the beam. The instruments on the rotating platform connect through a torsion harness to the fixed instrument platform. While the top of the instrument module, closed out with MLI, can see full solar illumination when the observatory points into the anti-Sun direction, some of the radial instrument radiators always point to cold space.

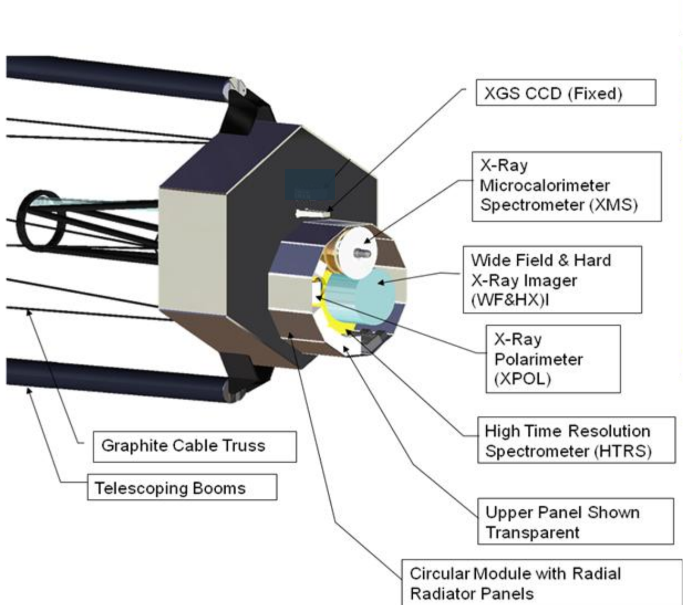


Figure 3. Alternate IXO instrument layout (MLI enclosures not shown).

5. INCREASED FIELD OF REGARD AND FOCAL LENGTH

5.1 Increased Instantaneous Field of Regard

One of the most fundamental capabilities of any observatory is the ability to slew to a science target of interest without hitting a slew limit or warning. In the observatory design this is the instantaneous field of regard. There is only one point in the observable sky that is an undeniable stay out zone, and that is the direction looking at the Sun. Some reasonable angular stay out zone must be maintained so that the telescope is not looking directly at sunlight, or receiving large amounts of stray light from the Sun. A typical (conservative) angle for this is assumed as a 45 degree conical half angle. For the L2 orbit selected, this stay out zone also includes the Earth and Moon. No other field of regard stay out zone exists. The resulting sun angles required to meet these needs are shown in Figure 4.

The solar array must be positioned to face normal to sunlight. This is accomplished with a single axis SADA while the spacecraft roll about bore sight provides the second axis required to point the solar cells normal to the Sun. Sunlight is shown as vertically downward for all spacecraft orientations in Figure 4.

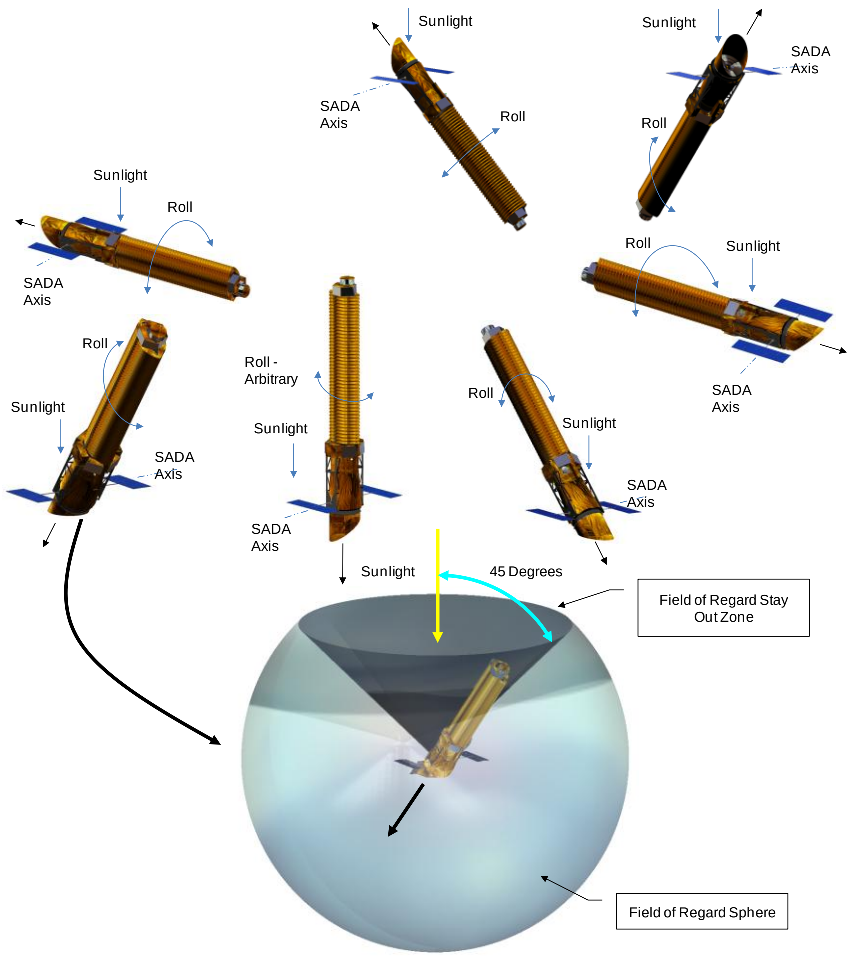


Figure 4. 3.41 πSR instantaneous field of regard spherical section and sunlight stay out zone

5.2 Observatory Focal Length

The observatory design readily achieves focal length range of 20 to 25 meters within expected mass and distortion requirements. This is made possible using the high stiffness to weight ratio provided by the tensegrity optical bench concept described in section 3. The longer focal lengths can increase effective mirror areas in key energy observing ranges such as 6 keV. This is done using the resulting decreased incident reflection angles over a larger percentage of the existing X-Ray Mirror assembly. Assuming a 6 keV critical grazing angle at a mirror radius R_{20}, the same 6 keV critical angle is found with the increased focal length of 25 meter at a mirror radius $R_{25} = R_{20}(f25/f20)$. The effective 6 keV mirror area increase is proportional to $(R_{25}/R_{20})^2$ provided that the mirror is a perfectly uniform collecting area design. The IXO concept has a key ACS feature (TADS) which provides optical bench metrology that occupies some of the central area of the mirror, thus removing some of the useful 6 keV area of the mirror for either focal length. This effective area loss is a larger percentage of the *f*20 mirror than the *f*25 mirror so the net area increase ratio is slightly stronger than a squared function ~ $(R_{25}/R_{20})^{2.16}$. The effective area for the hard X-Ray range of 30 keV can be increased in similar fashion while the lower energy range of 1.25 keV remains fairly constant assuming the outer diameter of the mirror remains the same.

6. THERMAL & STRUCTURAL ANALYSIS

6.1 Thermal Analysis

A key consideration for any space based telescope observatory is optical bench stability. Thermal distortion is a key concern when determining this stability. The increased field of regard for science observing also brings an increased variation in thermal profile that the optical bench (shown in Figures 1 and 2) must be designed for. A key design detail required to meet this is a complete and efficient multi-layer insulation (MLI) tent. The main objective is keeping the temperatures inside the MLI tent as constant as possible while the observatory is maneuvered over the large field of regard. Figure 5 shows the basic MLI tent concept as a cylindrical shape surrounding the internal optical bench. At the end facing the observed target line of sight, the MLI tent is open to space. This is the location of the X-Ray Mirror Assembly which is heated to maintain 20 ^{o}C. The opposite end of the MLI cylinder is closed, with only small openings at the instrument end of the tent for the focused X-Ray beam to pass through. The MLI tent is basically the shape of a deep cup.

Figure 5 shows the external MLI layer temperatures for both 90 and 180 degree sun angles, where 90 degree is normal to the telescope bore sight. Temperatures are evenly distributed along the length of the MLI tent for both sun angle cases shown, but a very pronounced temperature gradient exists around the circumference of the tent during 90 degree sun. A very efficient MLI tent design can reduce this circumferential gradient as much as an order of magnitude, where without the MLI tent, the optical bench itself would be directly exposed to this very large temperature gradient. The 180 degree sun angle case shows a fairly benign circumferential temperature gradient, but the bulk temperature is much cooler than the 90 degree case. Inside the tent the primary heat source comes from the X-Ray Mirror assembly which is maintained at 20^{o}C. The only thermal view that the internal optical bench has is of the inner MLI tent layer and the constant 20 ^{o}C X-Ray Mirror assembly. All avionics supporting spacecraft and instrument functions are kept external to the main MLI tent to minimize temperature fluctuation effects these might cause.

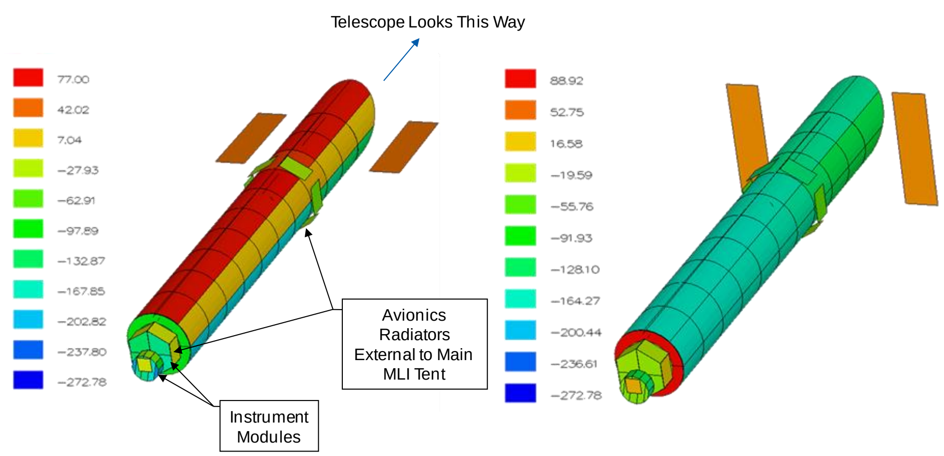


Figure 5. Outer MLI layer temperatures in 90 and 180 degree sun angle cases

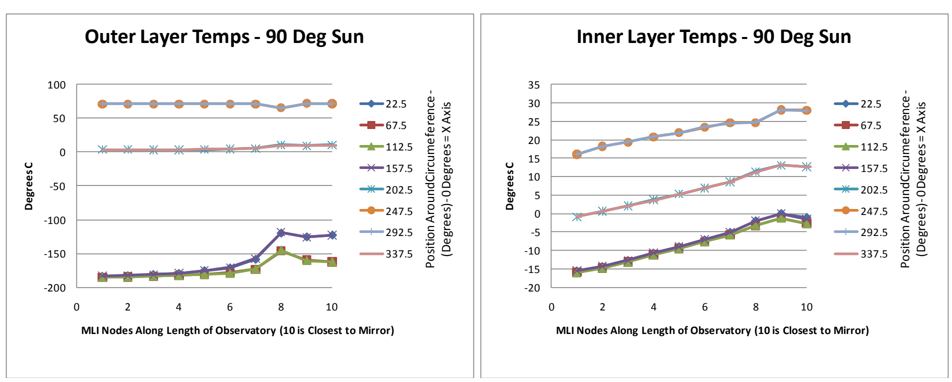


Figure 6. Outer and inner MLI temperatures for 90 degree sun angle

Inner Layer MLI temperatures can be compared to outer layer temperatures by studying the charts in Figure 6. The largest temperature variation from the 90 degree sun angle case occurs during the 180 degree Sun Angle case which is shown in Figure 7.

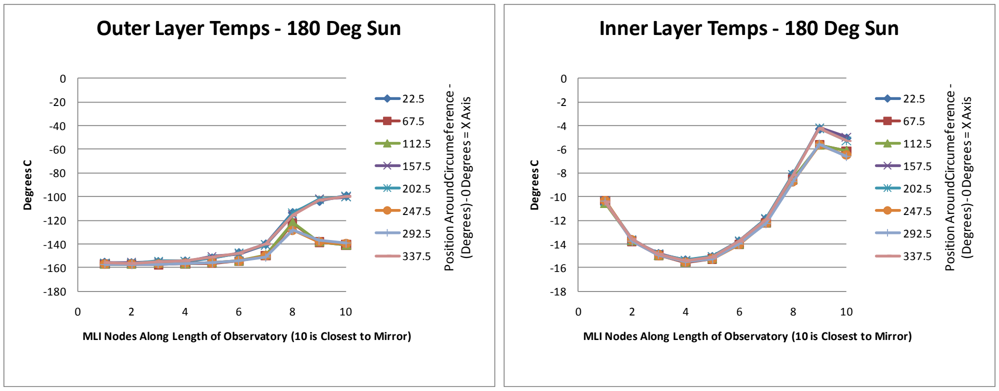


Figure 7. Outer and inner MLI temperatures for 180 degree sun angle

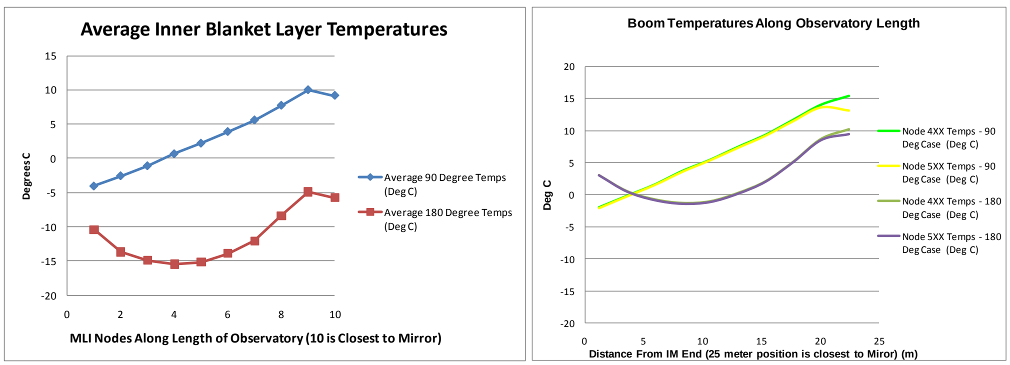
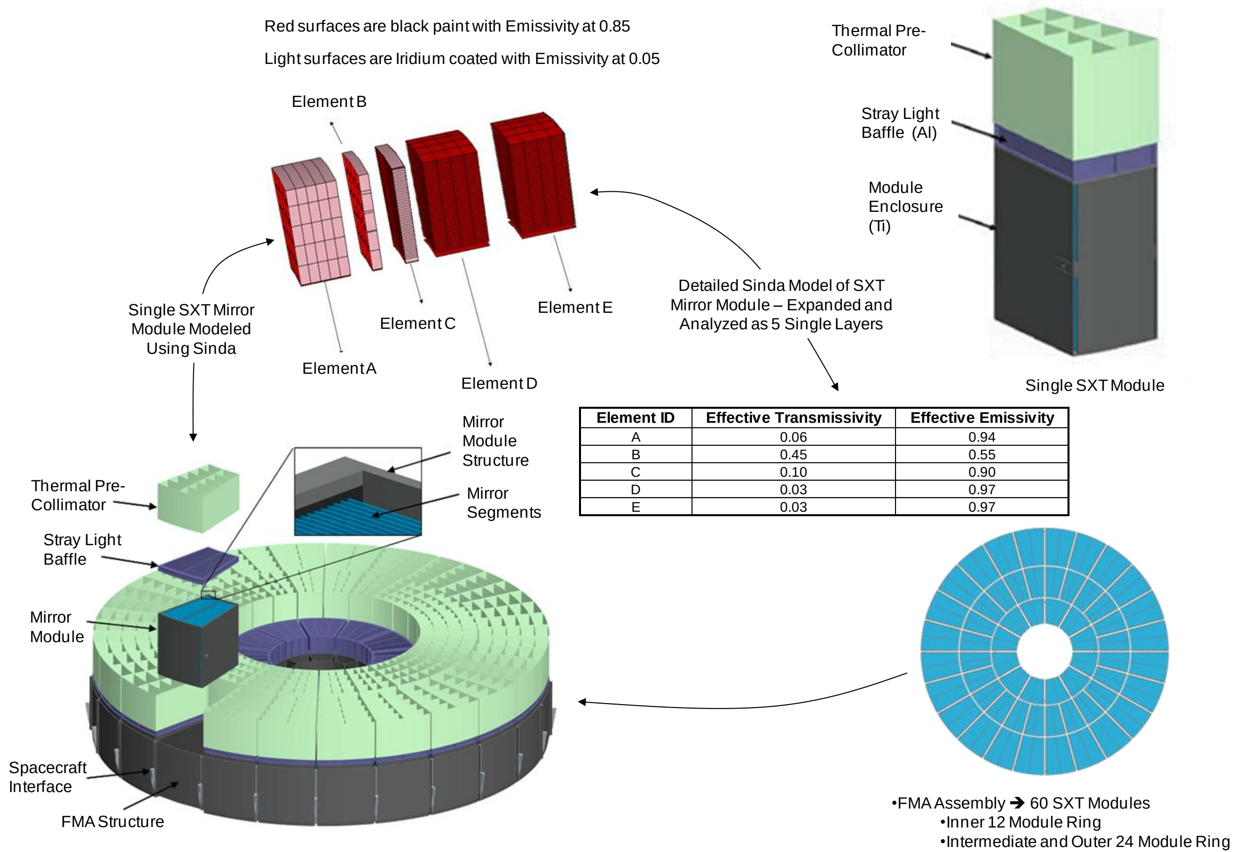


Figure 8. Average inner blanket temperatures (left) and boom temperatures (right).

Comparison with inner blanket layer temperatures shown in Figure 8 (left) shows the structural temperatures run cooler than inner blanket layer in the 90 degree case, indicating the heat is flowing in during the 90 degree sun case. Conversely the 180 degree boom temperatures are slightly warmer than the 180 inner blanket layer temperatures indicating the heat is flowing out during the 180 degree sun case. The main temperatures driving thermal distortion can be seen in Figure 8 (right) which shows both the 90 and 180 degree boom temperatures along the length of the observatory. We have incorporated carefully sized and placed passive radiators in our design to cool the 90 degree hot case and warm the 180 degree cold case, thereby bringing the two average structural temperature curves close together. The remaining difference shown in Figure 8 (right) has been minimized to an adequately small set of temperature changes, which when combined with an optical bench structure (described in 6.2) using a high percentage of near zero CTE materials, minimizes thermal distortion in the optical bench. It should be noted also, that no active heater control elements were required for the structural elements to achieve this, and very robust – long life blanket materials (all Kapton based) have been chosen to maintain this thermal design over the life of the observatory. This is a completely passive thermal design with the only heater control system being that within the X-Ray Mirror assembly.

The next major thermal analytical assessment is the effect of large sun angle change on the X-Ray Flight Mirror assembly or FMA [1,2]. A requirement of +/- 1 ^{o}C on FMA – SXT module to module temperature variation was checked. Figure 9 shows the basic FMA SXT module design concept and how this was simplified for analysis in the top level SINDA model of the observatory.



Element ID	Effective Transmissivity	Effective Emissivity
A	0.06	0.94
B	0.45	0.55
C	0.10	0.90
D	0.03	0.97
E	0.03	0.97

Figure 9. Simplification of FMA SXT module for SINDA observatory model

We first analyzed and expanded the individual SXT modules separately [3,4]. Based on this analysis we calculated the equivalent single layer properties for each of the components within the module. We then assembled these layers into a simplified model of the FMA Optics, as shown in Figure 10 and then integrated this simplified FMA Model into the top level observatory SINDA model shown in Figure 11. We now were able to calculate mirror temperatures as part of the SINDA sun angle analysis. We show a few early results in Figure 11.

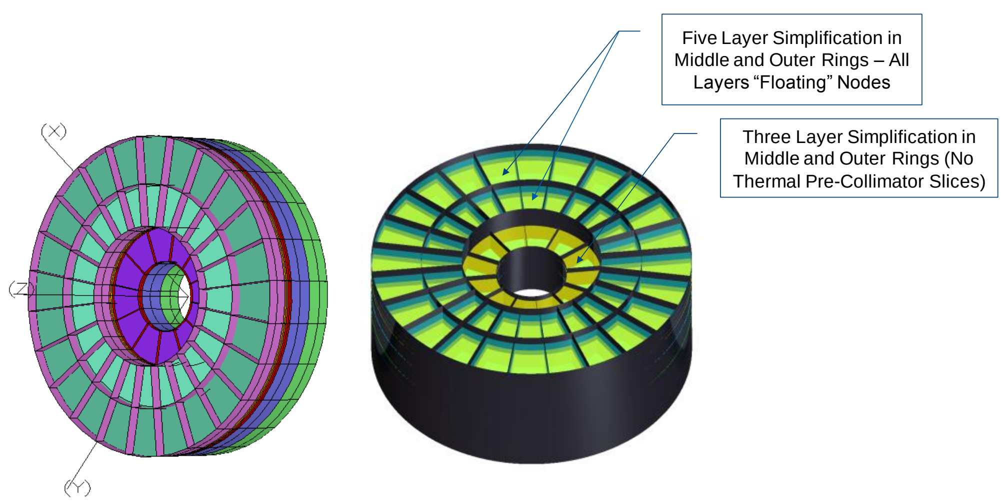


Figure 10. Simplified FMA optics module assembly – SINDA rendering (left) and solid model (right)

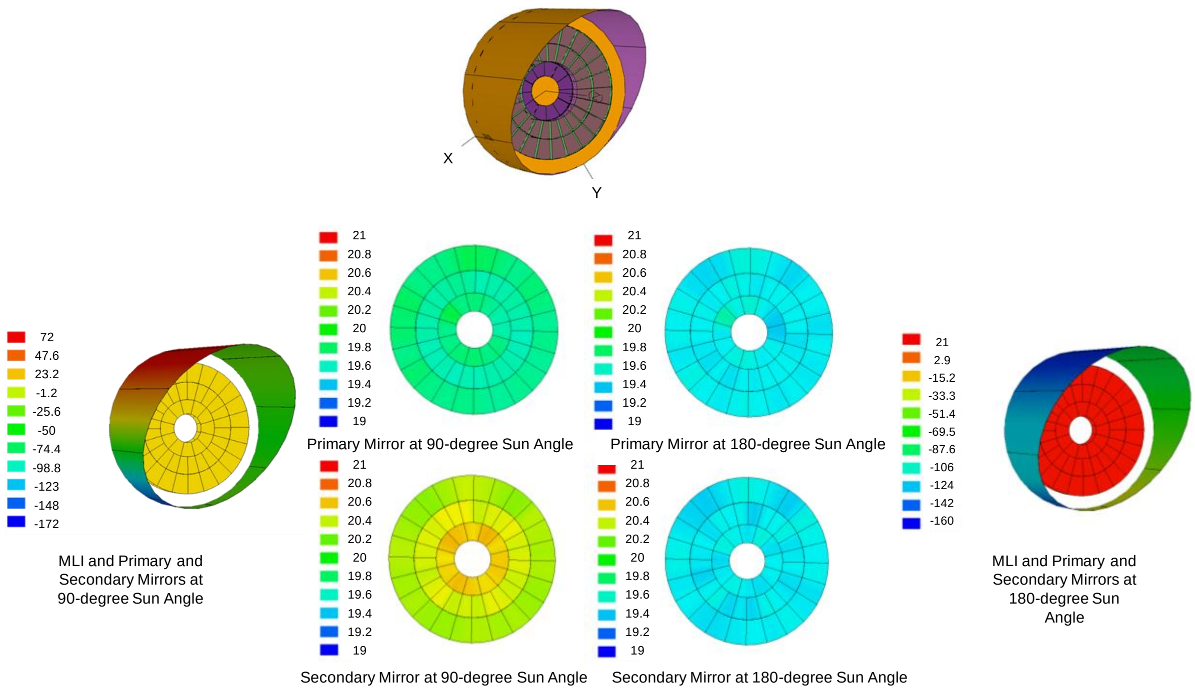


Figure 11. FMA installed in SINDA top level observatory – mirror temperature predictions

Spacecraft and instrument module avionics radiators have been analyzed over the large field of regard sun angle, and large radiator margins have been found indicating more than adequate cold bias is available for typical avionics powers assumed. Radiator outer surface properties assumed conservative end of life thermo-optical values for optical solar reflectors (OSR's - second surface mirrors). The radiators use baseplate mounted avionics with baseplate normal vectors pointing radially (in X-Y plane) in all cases except for the –Z pointed cryo-cooler pump ambient pump heat reject radiator. A trade is on-going between two types of cryo-cooler designs ranging from 164 watts to 360 watts heat rejection capabilities. Figure 12 highlights these radiators. In all cases avionics heat loads are MLI blanketed outside of the main optical bench tent for benefit of optical bench temperature stability.

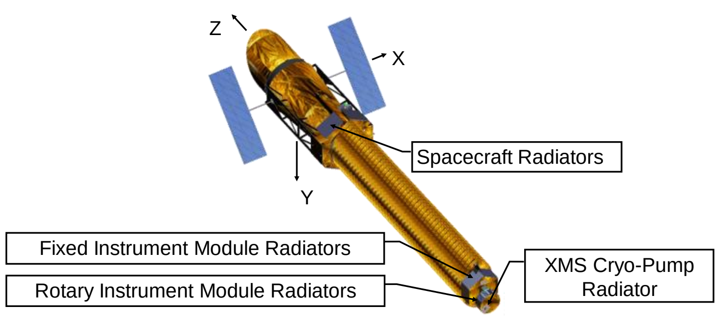


Figure 12. Radiator Analysis

6.2 Structural Analysis

We have used Finite Element modeling to show the very high deployed stiffness/frequency to weight ratio for the extendible optical bench concept. Key structural components have been modeled at the 25 meter focal length as shown in Figure 13. Preload has been simulated by using artificially added inertia in the tension lines to provide line modes simulating preloaded string modes. The structural concept uses a very high percentage of near zero CTE graphite, while minimizing lengths of metallic fittings. Preliminary thermal distortion results (using temperature data described in 6.1) indicate high positive margins against the requirements of 0.3 mm axial and 1.6 mm lateral distortion.

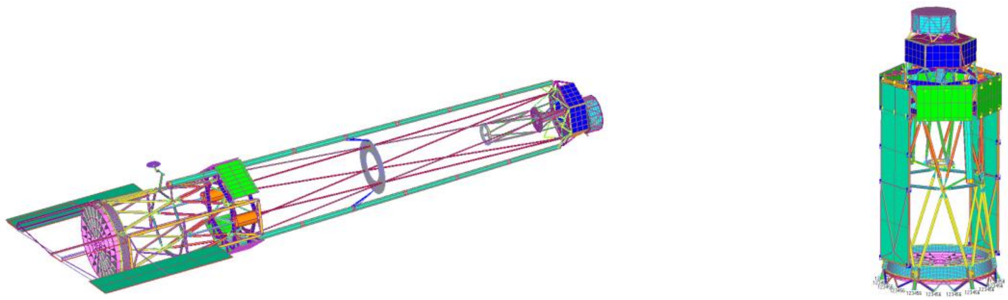


Figure 13. Deployed (left) and stowed (right) FEM's

Stowed finite element modeling has also been done showing the optical bench concept provides for very achievable launch strength/stiffness/frequency needs. This model is used to determine key launch constraint needs, such as launch locks required to meet basic stowed frequency and strength needs. At the base of the model is an adapter linking the 6 point IXO truss release system (via ultra low shock separation nuts) to the 18 point T4394 Atlas V – 551 Payload adapter truss. Preliminary strength margin checks show robust margins against typical launch loads. Preliminary mass estimates are based on correlations between the Femap models, Catia v5 solid models and excel based mass rollup files, and show a large mass margin above robust maturity based contingency levels (design maturity assed on a line item basis).

We have assessed the interface of the X-ray mirror assembly to the 6 point fixed truss section for the needs of a near zero CTE optical bench as well as launch strength requirements for this large observatory component. We assumed an 18 point launch adaptor (T4394) providing an integer adaptation to the 6 point fixed truss interface end. Launch loads from the 6 point fixed truss go directly into the booster adapter. 24 point pickup is provided for the X-Ray Mirror assembly to match the current GSFC mirror design. This design can accept the X-ray mirror assembly near the end of the integration and test phase to separate the development of the mirror and the optical bench as long as possible.. Figure 14 shows this interface.

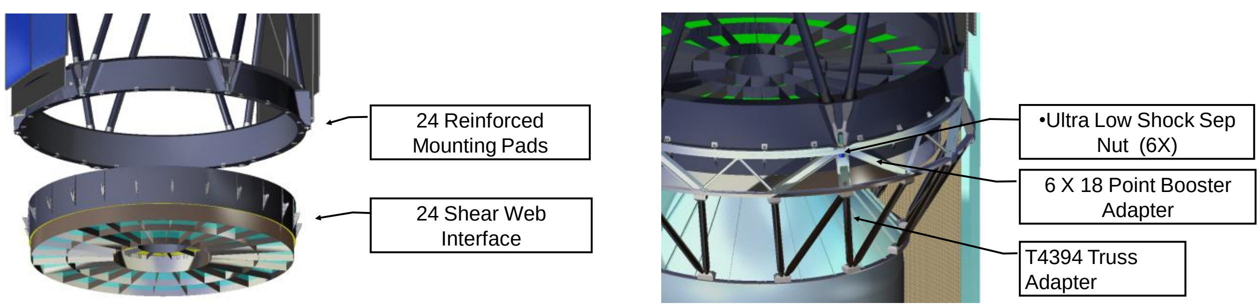


Figure 14. X-Ray mirror assembly interface with 6 point fixed truss

6.3 ADAMS Analysis

Automated Dynamic Analysis of Mechanical Systems (ADAMS) modeling has been used to determine key large angle-time dependent properties of the IXO optical bench system. We first assessed the ease with which the system can be balanced for solar pressure and center of mass alignment. This is a critical need for most large spacecraft, since momentum buildup in the ACS system occurs more rapidly in systems with large misalignments between the two. Momentum unloading is typically done by either firing thrusters in the opposite momentum direction, or spinning the spacecraft in an opposing solar loading configuration to accomplish the same effect. Both momentum unloading maneuvers are undesirable, and can usually be avoided with good alignment between center of pressure (CP) and center of mass (CM). Firing ACS thrusters frequently requires larger propellant mass loads, and results in undesirable dynamic oscillations that take time to settle. Observatory flip maneuvers are simply impractical if needed during an observation. The simplest observatory design practice is to align the center of pressure and center of mass as much as practical.

Figure 15 shows the method used to align CP and CM. The two boom tensegrity truss system permits a very narrow solar heating and loading profile in the 90 degree sun angle case. This moves the center of pressure closer to the X-Ray Mirror assembly, better aligning it with observatory CM. Final alignment tweaking is done using “trim tab” like width adjustments on the mirror sunlight cover. It should be noted that this can only be adjusted for one sun angle (assuming simple passive sunshade structure).

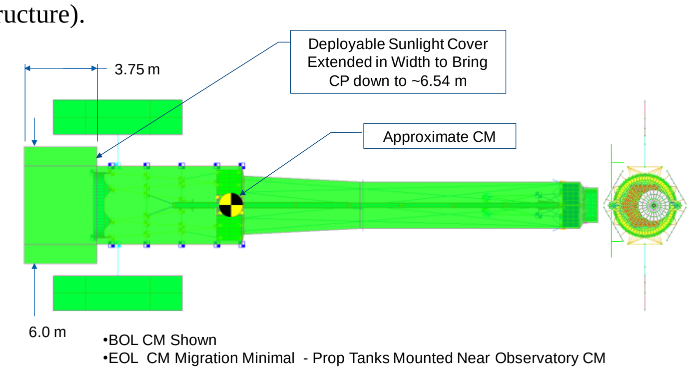


Figure 15. Aligning center of pressure and center of mass in the 25-meter Observatory

Next we broke down the solar force components into three very basic elements: (1) Solar array loads, (2) MLI tent loads (normal and shear) and (3) instrument module end loads (normal and shear). Figure 16 shows the basic concept used in this simplified early assessment for momentum buildup over sun angle. Figure 17 (left) shows the simplified analytical results. We note that for this first assessment we approximated the accordion folds with a simple flat plate. We have not yet modeled the full complexity of the multiple accordion bellows, which might have a significant impact on the result of this analysis.

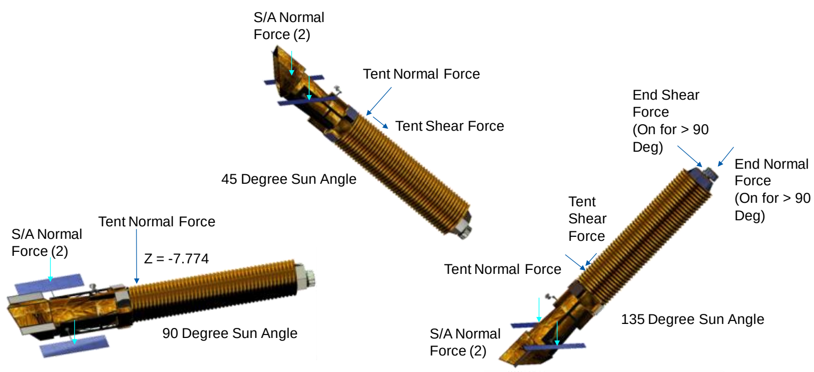


Figure 16. Solar pressure loading cases

Even in the largest momentum buildup case at 45 degree sun angle, the momentum buildup results are low compared to the individual wheel capacity of 150 N-m-Sec – even after several days of observations. The largest buildup occurs when the observatory is pointed to within 45 degree of the Sun. In this case, the balancing effect of the instrument module loading goes into shadow and is lost. More detailed study is needed before final margins can be assumed.

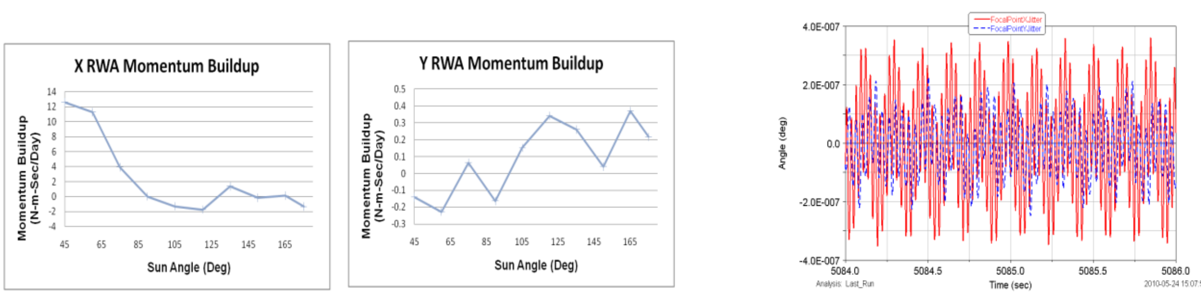


Figure 17 – Solar pressure momentum buildup versus sun angle (left). Focal point jitter (right).

Also key to satisfying the IXO needs at longer focal lengths is Jitter analysis. ADAMS modeling checks include preliminary jitter checks against the 5.5 10^{-5} degree (200 milliarcsecond) over 200 millisecond span time. Figure 17 (right) shows an example case with large positive margin against this requirement. Much more analytical jitter checking is needed to cover worst wheel speed combinations and verify basic modeling frequency and damping assumptions as well as wheel imbalance assumptions.

Another Fundamental ADAMS check required to satisfy longer focal length designs is slewing speed. A four wheel pyramid using HR16-150 reaction wheels [5] is modeled and slewing times satisfy the IXO mission requirement of 60 degree in 60 minutes. Figure 18 shows a 60 degree slew in right ascension (left) as well as a 60 degree slew in declination (right). Both assume zero wheel speed starting points. Wheel speeds were held conservatively to about 30,000 degree/second as shown in Figure 18 (center), compared to standard ratings of 36,000 Deg/Sec (6,000 RPM). The rotors themselves are rated to 10,000 RPM. We have also animated these slews in ADAMS, with side by side wheel speeds to visualize these various types and ranges of slewing maneuvers.

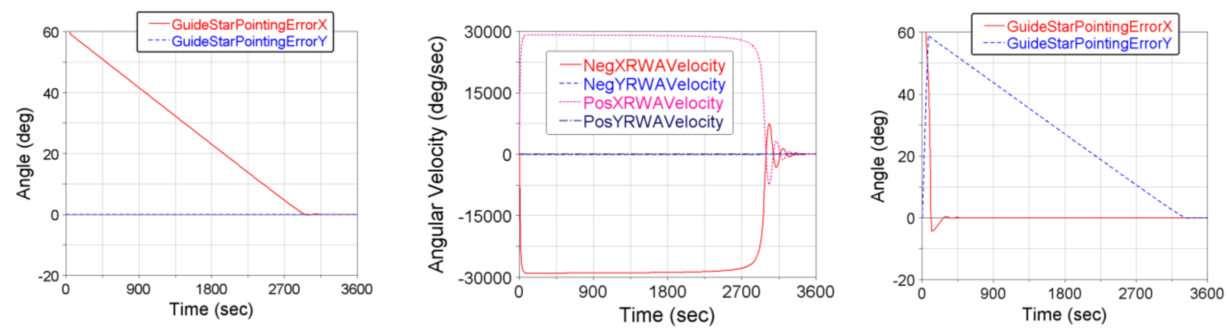


Figure 18. 60 degree slew in RA (left); RWA speeds during 60 degree slew in RA (center); 60 degree slew in declination (right)

6.4 System Analysis

Our preliminary mechanical system analysis indicate that our goals of increasing the science return of the mission and reducing technical and cost risk are feasible. A high level of confidence in concept has been achieved through internal research and development efforts with an emphasis on the space-vehicle system interactions described.

The observatory uses heritage hardware to implement a cost-effective, low-risk approach. We find that we can achieve a 24.8% margin on an Atlas V 551 launch vehicle in the 25-m configuration, and a 27.6% margin in the 20-m configuration. The maximum power load requirement of the observatory is 5200 W at end of life, against which our design holds a 15.4% margin.

The spacecraft provides power, communications, propulsion, attitude control, and command and data handling for the observatory and thermal control for the spacecraft itself. The spacecraft also serves as the primary interface between the FMA and Optical Bench, and controls deployment of the optical bench. The spacecraft structure is a truss design with six modular equipment panels, two of which provide the structural support for the solar arrays. All components of the spacecraft have heritage from previous missions.

7. IMPLEMENTATION

7.1 Sub-scale Mechanical Model

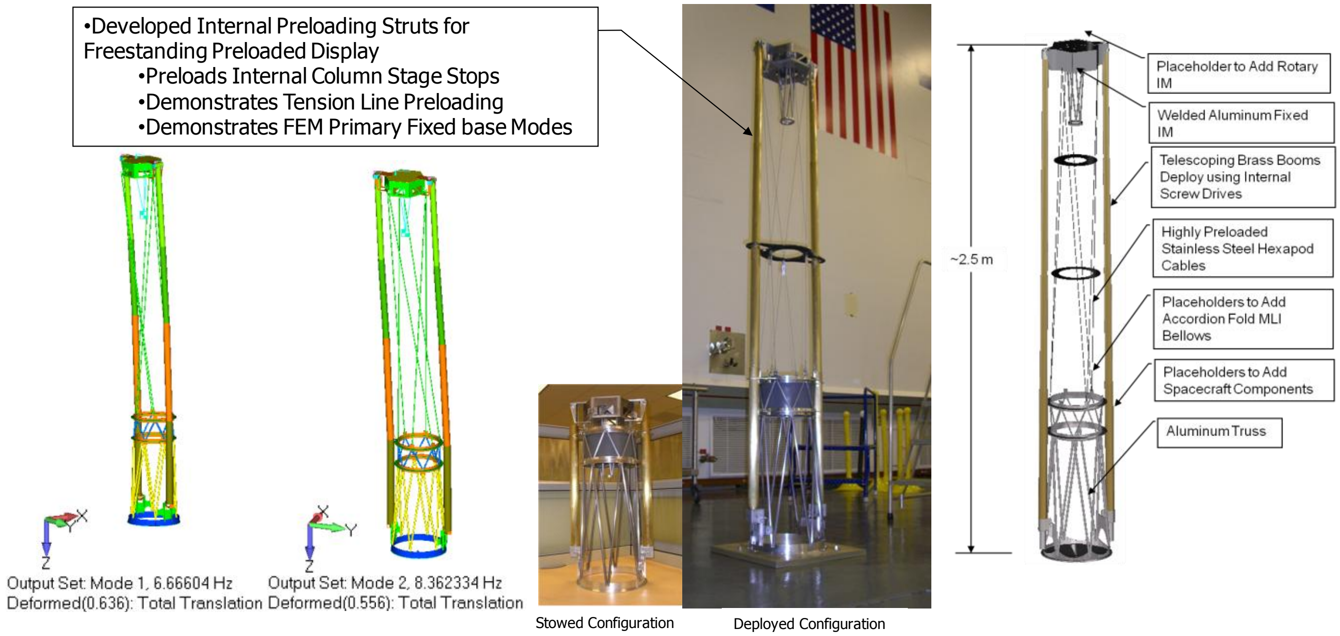


Figure 19. 1/10th Scale IXO tensegrity structural modeling

In 2009 we developed a 1/10 scale engineering model to demonstrate the deployment concept and to become familiar with the structural properties. For cost and schedule reasons, the model was developed from aluminum, steel and brass components. Currently planned upgrades include incorporating deployment motors and control electronics. While the deployment motion was assisted with overhead crane instead of internal drive, the motion is the same and was documented with video and approximate tap test. Figure 19 shows the tensegrity optical bench in the 1/10th scale that it was modeled. While no test instrumentation was installed to record modes, observed modes were closely in line with prediction.

7.2 Deployable Astro Boom

The two primary deployment booms are derivatives of the Astro Aerospace Telescopic Boom [6]. This boom is comprised of a set of highly efficient, thin walled, large diameter, graphite, latching booms with an internal deployment drive system using the well proven STEM (Storable Tubular Extendible Mechanism). The STEM itself is capable of a 150 lbf deployment force and is supported within the set of telescopic tubes to prevent buckling as it reaches its extended length. Deployment stage sequencing and integration and test features such as self retracting have been incorporated into the subsystem design and tested on full scale development models. The entire boom system has undergone several design refinement cycles with system level testing which has brought it to a high TRL6 development level. This subsystem is currently in the engineering production cycle on JWST scheduled for a 2014 launch.

7.3 Deployable Instrument Module Harness

An enabling technology for IXO is the deployable harness assembly. We're considering using one of two typical harness deployment management concepts. Both helical and clock spring coil arrangements are the subject of on-going trade studies to determine the lightest and most robust cable management system.

8. SUMMARY & CONCLUSION

Moving IXO from the drawing board to the launch pad will take more than just engineering ingenuity. It is critical that the best technical solution is evaluated against what is realistically achievable within the available budget and schedule. For this reason, we have developed our concept based on existing technology that combines flight proven elements in innovative ways, but does not require extensive technology development. We further hope that this paper illustrates the experience that is brought to the team by engaging early with an experienced industry team. By drawing on the best talents from NASA, international partners, academia and industry, IXO will become reality within budget and on schedule.

9. REFERENCES

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